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Safeguarding reforestation efforts against changes in climate and disturbance regimes

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ABSTRACT

Reforestation schemes, which encompass environmental plantings and natural regeneration of vegetation on cleared land, are increasingly being established for the purposes of mitigating anthropogenic carbon emissions. However, these schemes are themselves at risk from climate change and associated changes in disturbance regimes. Simultaneously, there is increasing pressure on reforested areas to achieve multiple co-benefits, e.g. maximizing carbon storage, ameliorating environmental degradation and promoting biodiversity objectives, all while not adversely affecting community values, such as agricultural production. Here, we review the myriad of biophysical risks posed by climate change to reforested areas while documenting management actions and policies that can enhance both the resistance and resilience of reforested areas to such risks. While it is difficult to buffer vegetation against the direct effects of climate change, such as elevated temperature and changed precipitation patterns, it is possible to manage some of the indirect effects, such as wildfire, drought and insect defoliation. Methods for reducing the vulnerability of reforested areas range from site-specific management actions, particularly around design and location, through to regional and national scale initiatives, such as vulnerability assessments and decision support tools. The complexity of objectives and risks posed to reforested areas means that it is vitally important to evaluate outcomes from across the current estate of reforested areas. However, there is currently no national protocol in place in Australia to track, monitor or evaluate the outcomes of reforestation. Thus, we recommend the establishment of a national framework for analyzing and supporting the growing range of reforestation activities.

1. Introduction

The widespread establishment of environmental plantings and other forms of reforestation are being targeted by many governments to mitigate increasing levels of atmospheric carbon dioxide (Hulvey et al., 2013; Australian Government, 2014; United Nations, 2016). Compared to other abatement opportunities, carbon offsetting through reforestation may provide valuable mitigation opportunities at relatively low cost (Tavoni et al., 2007). Historically, non-commercial forest plantations have been established to provide a range of landscape services other than carbon abatement, including shelter for livestock, improved landscape amenity, and the amelioration of environmental problems such as dryland salinity and water quality issues caused by erosion and nutrient runoff (Cunningham et al., 2015). More recently, the purpose of reforestation has been broadened to include a suite of environmental services including reduction or reversal of landscape biodiversity losses (Cunningham et al., 2015). A number of recent studies have highlighted the potential opportunities for reforestation globally, including in Australia (Paul et al., 2013; Griscom et al., 2017), Brazil (Shimamoto et al., 2014) and the USA (Sharrow and Ismail, 2004).

Longevity is a key requirement to achieve many of the current objectives for reforested areas (United Nations, 2016). This is embodied in regulatory requirements such as permanence (e.g. 100 years; Australian Government, 2014). These requirements mean that reforested areas must be robust to risks and viable over long time periods. Drought, fire, pests and grazing pose biophysical risks, while changing land regulation and opportunity cost may affect the economic viability of reafforestation (Kragt et al., 2017; Nolan et al., 2018a, 2018b). A disruptive issue

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facing reforested areas is climate change, which is likely to affect the frequency and severity of disturbances, and rates of vegetation growth (Nolan et al., 2018a). Thus, climate change is likely to have important consequences for carbon sequestration rates and may adversely affect provision of environmental services. Once environmental plantings are established, there are few options for adaptation to climate change (Millar et al., 2007). Assessment of the risks posed by changing climate and disturbance regimes over the lifetime of reforested areas during the planning and design stages is critical.

Climate change will generate local effects on tree growth and survival, but will also have effects at regional and national scales over which disturbances and risks occur. Reducing risk to reforested areas is likely to be best achieved if there is co-ordination of risk mitigation strategies at scales larger than individual project boundaries (Nolan et al., 2018a) and would be assisted by a co-ordinated regional or national scale framework for managing reforestation that geographically disperses risk.

In this paper, our objectives are to (i) identify the vulnerabilities of reforested areas to climate change and associated changes in disturbance regimes; (ii) identify mechanisms to reduce the vulnerability of reforested areas to climate change; and (iii) evaluate the role of decision support systems and modelling in managing the reforestation estate at a national scale. As part of our review, we present a case study on the use of vegetation established for carbon abatement in Australia.

2. Defining reforestation

Here, the term 'reforestation' is an umbrella term used to refer to all types of woody vegetation established for environmental purposes. This includes vegetation established from planted seedlings or from directly sown seed. We also include human-induced regeneration, which is where natural regeneration of vegetation on cleared land is facilitated by a change in land management, for example by fencing to remove grazing by livestock and wild herbivores. Reforestation encompasses a spectrum of environmental, social and economic objectives. Reforested areas may incorporate multiple-species of trees and shrubs established from either plantings, natural regeneration, or regrowth from rootstock. They are often established for long periods and for one or more objectives, e.g. carbon sequestration, flood mitigation, erosion control, biodiversity conservation and other landscape benefits (e.g. aesthetics). Although they may be established in different ways, in reality all reforested areas, whatever their primary goal, have the capacity to yield a range of co-benefits as well as dis-benefits.

3. Vulnerability of reforested areas to changing climate

Vulnerability is 'the degree to which a system is susceptible to, or unable to cope with, adverse effects of change' (IPCC, 2013). It is a function of exposure to unfavourable conditions and the sensitivity of the system to those conditions, which collectively define impact (Fig. 1). Vulnerability varies across systems, depending on their adaptive capacity to adjust to change or cope with the consequences of change.

3.1. Exposure

Climate plays a major role in shaping the distribution and composition of forests (Engelbrecht et al., 2007). It follows that the direct and indirect biophysical effects of climate change will pose challenges to reforested areas in the future (Table 1). Increases in maximum and minimum temperatures are projected for most regions of the world, with projected global average warming at the end of the 21st century ranging between 1.1 and 6.4 °C (IPCC, 2013). All climate models predict changes in global mean precipitation as a consequence of the intensification of the global hydrological cycle, with increases likely in the tropical and higher latitude regions and decreases likely in subtropical and mid-latitude regions (IPCC, 2013). Associated with these broad-scale trends is an expected increase in the frequency, duration and intensity of droughts and heatwaves, as well as reductions in relative humidity (IPCC, 2013).

Extreme climate events and their associated disturbances play a key role in fine scale patterning of species distributions (Reyer et al., 2013), and can thus have an important influence on the long-term survival of reforested areas. In particular, forest mortality events can be triggered by droughts and heatwaves (Mitchell et al., 2014), extreme storm events, e.g. cyclones (Kanowski et al., 2008) and from increases in the frequency and intensity of wildfires (Flannigan et al., 2009; Bradstock, 2010). There are also strong links between climate and the abundance and distribution of forest pathogens and insects that reduce productivity or contribute to mortality (Kurz et al., 2008).

Changing global climate is likely to have both positive and negative effects for reforested areas. In temperature-limited environments, warmer mean annual temperatures may increase growth due to lengthening of the growing season (Vitasse et al., 2011). This may increase the potential distribution of species currently restricted by mean minimum temperatures, provided dispersal is not limited. However, changes in litter layers associated with climate-induced changes in the ratio of production to decomposition may change the fire hazard. Warmer temperatures may also result in higher rates of transpiration, leading to water stress (Duan et al., 2014); reduced frost hardening, leading to more severe frost damage when these events do occur (Woldendorp et al., 2008); and increased pressure from pathogens, many of which favour warmer conditions (Sturrock et al., 2011). In contrast, reduced precipitation in subtropical and mid-latitude regions may reduce growth rates and growing season length, affecting seed production and recruitment success (Suarez and Kitzberger, 2008). Increased atmospheric CO_2 may lead to a "fertilization effect" that increases productivity, particularly in drylands (Donohue et al., 2013). However, any increases in productivity may be offset by increases in extreme climate events, while changes in atmospheric CO_2 may also alter the balance of grassy, shrubby and tree life forms through differential changes in water use efficiency (Polley et al., 1994).

3.2. Sensitivity

The sensitivity of reforested areas to changes in climate and associated disturbance regimes is a function of both their resistance and resilience to disturbance. Resistance is defined as the capacity of a system to absorb a disturbance without major loss, whereas resilience is the capacity to recover from severe disturbance (Lake, 2013). The resistance and resilience of environmental plantings will vary as a function of species composition, diversity, and within-species genetics. Following disturbance, some species are more susceptible to mortality than others. For example, high intensity fire kills some species whereas others are capable of resprouting (Clarke et al., 2013). Some fire-killed species have adaptations that enable them to persist locally through fire-stimulated recruitment (Clarke et al., 2013). Indeed, some reproduction strategies require fire to promote regeneration. Resprouting can also occur following other disturbances such as drought, windthrow or herbivory, a strategy utilized by a diverse range of species globally (Vesk and Westoby, 2004).

Further adaptations to drought, or periodic water stress, include a suite of plant traits which confer drought tolerance. These include anisohydric stomatal behaviour, where stomatal conductance during soil drying remains unregulated (compared with isohydric behaviour where there is tight regulation of stomatal conductance; Tardieu and Simonneau, 1998). By keeping stomata open, anisohydric species are able to continue fixing carbon and avoid the potential carbon starvation that would otherwise occur during drought (McDowell et al., 2008). These species typically possess a range of adaptations to low soil moisture, including a high degree of resistance to xylem embolism, small leaves and low specific leaf area (Brodribb et al., 2014, Nolan

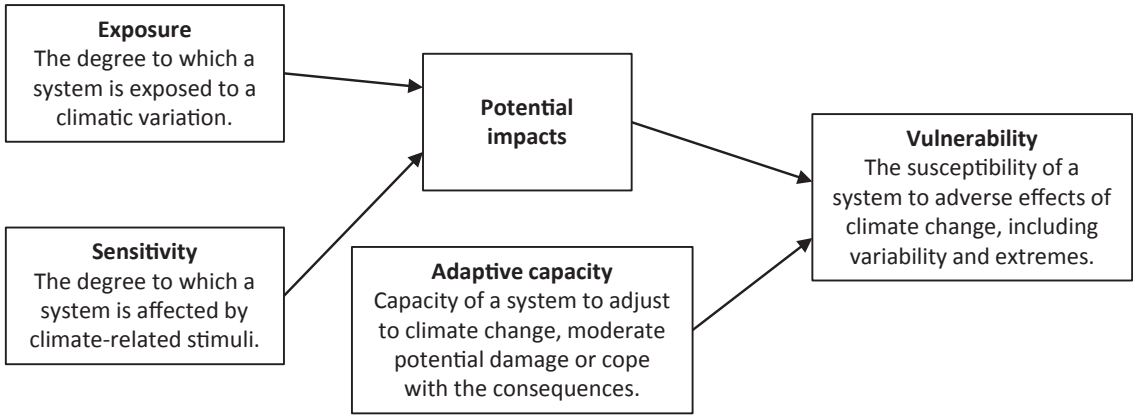
Exposure
The degree to which a system is exposed to a climatic variation.
Potential impacts
Vulnerability
The susceptibility of a system to adverse effects of climate change, including variability and extremes.
Sensitivity
The degree to which a system is affected by climate-related stimuli.
Adaptive capacity
Capacity of a system to adjust to climate change, moderate potential damage or cope with the consequences.

Fig. 1. The impacts of climate change on reforested areas are a function of exposure to unfavourable climatic conditions, and the sensitivity of the vegetation to those conditions. These collectively determine the vulnerability of the system. However, vulnerability can be modified with the adaptive capacity of the system. Adapted from the Australian Greenhouse Office (2005).

et al., 2018b). These drought tolerant species contrast with drought avoiding species, which can effectively avoid seasonal dryness through access to groundwater or drought deciduousness. These species typically exhibit relatively high specific leaf area and large xylem vessel diameters (Choat, et al., 2005; Nolan et al., 2018b). Other drought responses include adjustments to biomass allocation, such as increased root growth, or leaf shedding, resulting in an increased root:shoot ratio that reduces exposure to water stress (Ledo et al., 2018). Similarly, adaptations also occur in response to herbivory and pathogens, including traits such as leaf toughness, nutrient content and defence compounds (Schuldt et al., 2017). However, sensitivity to herbivory and pathogens may be exacerbated by prevailing environmental conditions. For example, plants may be more sensitive to pathogens if water stressed (Sturrock et al., 2011), or under elevated CO_2, at least for some species of herbivores, although the impact of elevated CO_2 remains uncertain (Robinson et al., 2012).

Genetic variation among individuals and populations is an additional consideration. For example, plants from relatively arid climates often exhibit greater drought resistance than plants from cooler and wetter climates when grown under the same environmental conditions (Bansal et al., 2015). Similarly, there is evidence that plants from drier populations have greater capacity to resprout following disturbance than plants from wetter populations (Borzak et al., 2016, Ladiges, 1974). Given the range of traits across species that confer adaptation to different disturbances, diversity in plant species composition, within-species genetics and functional traits within plantings is likely to increase resistance and resilience to changes in climate and associated disturbance regimes.

3.3. Vulnerability through time

The vulnerability of reforested areas varies temporally as functional attributes of vegetation change with ontogeny, i.e. as tree size and age and stand density changes. One of the largest hurdles for reforestation projects is establishment. Seed germination and survival are dependent on climate and associated disturbances, in particular, the conditions required for natural regeneration can be infrequent and difficult to predict (Vesk and Dorrough 2006). Newly established reforested areas are inherently vulnerable to drought until trees establish adequate root systems (Fig. 2a), after which vulnerability declines. Vulnerability is also higher when a stand reaches maximal leaf area index, due to competition for water (White et al., 2009). Small trees are most vulnerable to fire-induced mortality when they have thinner bark which provides less insulation (Fig. 2b; Vines, 1968).

Vulnerability is also dependent on the attributes of a disturbance regime, specifically frequency, intensity and duration. Increased frequency of high intensity wildfires can reduce the capacity of forests to regenerate, and may result in widespread forest mortality (Fairman et al., 2016). Co-occurring disturbances can have antagonistic, additive or synergistic effects that may increase or reduce vulnerability compared with single disturbance events (Mitchell et al., 2013). For example, vegetation is often more vulnerable to insects during drought (Jacquet et al., 2014). Conversely, a disturbance that reduces leaf area at the time of maximum leaf area index, may reduce vulnerability to subsequent drought events (Fig. 2a; Mitchell et al., 2013). It is plausible that low intensity disturbance events may actually reduce vulnerability in environmental plantings. This may occur through a range of acclimation processes (e.g. osmoregulatory compounds and defence chemicals) that enhance resistance to subsequent disturbance events (Markham, 1996; Nolan et al., 2017). Over longer timeframes (multiple generations), such adaptations may result in genetic changes to populations which make vegetation more resilient (Markham, 1996), although this is most likely to occur in intact natural stands, and be less relevant to environmental plantings that are relatively isolated in more fragmented agricultural landscapes. Thus, frequent disturbances over time may either reduce vulnerability to biophysical risks via

Table 1
Trends and projections of global weather and climate events. Only variables for which there is evidence of an observed late 20th century trend are included. From Nicholls (2008). Likelihood terminology: "virtually certain" means > 99% probability; "very likely" means > 90%, but < 99%; "likely" means > 66% but < 90%; "more likely than not" means > 50%.

Phenomenon and direction of trend	Likelihood that trend occurred in late 20th century	Likelihood of future trend based on projections for 21st century
Warmer/fewer cold days/nights over most land areas	Very likely	Virtually certain
Warmer and more frequent hot days/nights over most land areas	Very likely	Virtually certain
Increased frequency of heatwaves over most land areas	Likely	Very likely
Increased frequency of heavy precipitation events	Likely	Very likely
Increased area affected by drought	Likely in many regions since 1970	Likely
Increased intense tropical cyclone activity	Likely in many regions since 1970	Likely

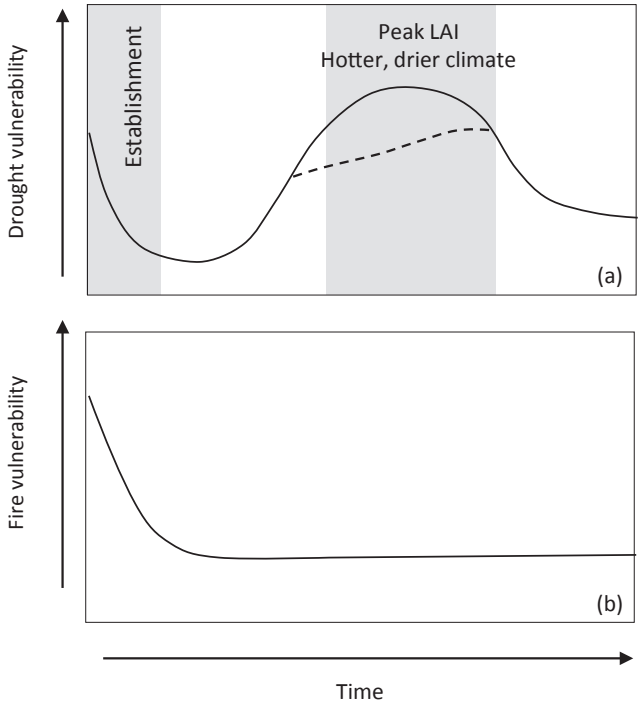

Fig. 2. Temporal changes in vulnerability of reforested areas to (a) drought and (b) fire. Key periods of drought vulnerability occur at establishment and at the period of peak leaf area index (LAI). Drought vulnerability may be reduced by disturbance events, for example fire or biotic damage that reduces leaf area (dashed line). Fire vulnerability peaks at early stages of plantings when fire spread is likely to be faster and rates of mortality higher.

acclimation processes, or increase vulnerability to these risks due to accumulation of stress, depending on the type, intensity and duration of disturbance.

Climate change and associated disturbances may also affect the value of environmental services delivered by forests. For example, in the absence of climate change or disturbance, rates of carbon sequestration increase rapidly and then plateau as a planting attains maximum leaf area index (Fig. 3; Grierson et al., 1992), declining in the longer term as stand productivity declines. Rates of productivity may decline further, however, under unfavourable conditions such as reduced mean annual precipitation (Mitchell et al., 2016; Fig. 3). Likewise, high intensity drought or temperature stress may drive large carbon emissions due to dieback or widespread mortality (Ciais et al., 2005), re-setting the trajectory of carbon sequestration (Fig. 3). The importance of this

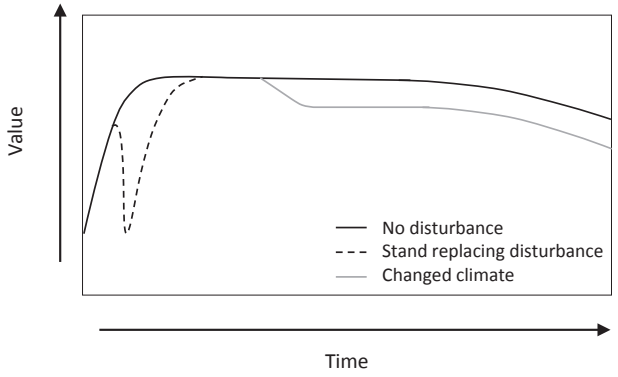

Fig. 3. Theoretical trajectory of the value of a reforestation project for carbon sequestration without disturbance; following a stand-replacing disturbance, such as wildfire; or following changed climatic conditions, such as a reduction in mean annual rainfall.

disturbance-driven devaluing will vary with age of the planting. For example, a disturbance event that results in widespread mortality early in the life of a reforested area will result in lower carbon emissions than in a mature forest. Conversely, less intense disturbances such as low intensity drought are likely to impact more on younger forests because of their shallower roots. Early disturbance events may drive reductions in carbon sequestration followed by recovery to the same or similar trajectory, or may result in a change in the slope of the sequestration curve if recruitment processes or management intervention do not occur post-disturbance (Fig. 3).

As reforested areas age their incremental value for carbon sequestration gradually declines, driven by an age-related lowering of productivity (Fig. 3; Ryan et al., 1997). Observations of declines in productivity with tree age may be due to multiple factors, including reduced leaf to sapwood area ratios, and increased tree height reducing rates of transpiration (Ryan et al., 1997; Delzon and Loustau, 2005). While the incremental value of reforested areas for carbon sequestration in biomass may decline over these longer time-periods, other values continue to increase. For example, large tree hollows, an important habitat resource for many mammals and birds, can take upwards of 100 years to develop (Vesk et al., 2008). Furthermore, mature-aged stands of trees typically have greater recreational and/or aesthetic value than stands of young trees (Blasco et al., 2009; Keenan and Read, 2012), directly influencing land values (Polyakov et al., 2015). Likewise, although older stands may sequester carbon at reduced rates, their carbon stores remain high.

4. Reducing the vulnerability of reforestation

Managing the vulnerability of reforested areas to climate change centres on two key approaches. The first approach is to try and manage exposure to disturbances, where possible. The second approach is to promote the resistance and resilience of plantings to both direct climate change effects and to changed disturbance regimes. The second approach is preferable since, over long timeframes, an ecosystem with high resistance is able to maintain its composition, structure and ecological function (Thompson et al., 2009). While reforestation occurs for a range of primary purposes and co-benefits, there are a number of principles that can be applied across the range of reforestation activities that may reduce their vulnerability to global environmental change and associated disturbance events. These principles range from decisions at the scale of individual projects encompassing planting design, species selection and management interventions following establishment; to landscape or regional scale decision-making and policy approaches for managing reforested areas. In this section, we discuss options for mitigating the effects of disturbances on reforested areas across this range of scales.

4.1. Designing reforestation projects

Because reforestation projects are generally intended to persist over long timeframes, the design stage is critically important. Careful planning can minimise the need for later management interventions and maximise the likelihood that desired goals are achieved. The design phase requires consideration of species composition, establishment method(s) and spacing, targeted vegetation structure, and the size and location of plantings. These design considerations are important for both buffering reforested areas and in enhancing their resistance and resilience to disturbance (Table 2).

4.1.1. Species mix and within species genetic variation

Selection of the most appropriate species, or combination of species, and their genetic provenance, is critical to establishing reforested areas with low vulnerability to climate change (Breed et al., 2013). These decisions will depend upon the objective of the reforestation project. For example, biodiversity plantings will often target a mix of species,

Table 2
Overview of methods for reducing vulnerability of reforested areas, and the spatial scale they can be applied across. These methods can either buffer (B) the reforested areas (i.e. reduce exposure) or enhance the resistance and resilience (R) of the reforested areas to climate change and associated disturbances.

Risk reduction method	Site	Landscape	Regional/ national
Designing reforestation projects			
Species and seed provenance selection	R		
Stand density	B/R		
Structural complexity (e.g. trees and shrubs)	R		
Age structure	R		
Size and shape	R		
Location	B/R	B/R	B/R
Timing of reforestation (seasonal weather forecasts)	B		
Establishment methods	B		
Established reforestation projects			
Fire prevention	B	B	
Thinning	R		
Planned disturbances	B/R		
Grazing management	B/R	B/R	
Regional and national approaches			
Vulnerability mapping		B	B
Vegetation mapping		R	R
Monitoring and communication			B/R
Decision support tools and models	B/R	B/R	B/R

providing habitat and foraging resources for a range of fauna (Munro et al., 2009). In contrast, carbon plantings have often targeted fast-growing tree species, with low species diversity (Chazdon, 2008). However, recent evidence suggests that diversity in species can have similar or higher rates of carbon sequestration than monocultures (Forrester et al., 2006; Hulvey et al., 2013; Forrester, 2014), driven by complementary resource use between species, e.g. root stratification, or by including nitrogen-fixers that increase the overall biomass of plantings (Kelty, 2006; Hulvey et al., 2013). Furthermore, a diverse species mix enables environmental plantings to meet multiple objectives, e.g. carbon abatement, site remediation and biodiversity benefits (Maestre et al., 2012; Paul et al., 2016).

Multi-species plantings do more than just delivering on multiple objectives, they also facilitate enhanced resistance to climate change and associated disturbances. For example, multi-species plantings are often more resistant to disease and pest damage (Hulvey et al., 2013). Ecosystems with a high diversity of species have an enhanced capacity to resist disturbances because of the differing range of responses to disturbances (McCann, 2000). Thus, diversity in functional traits is vital in reducing the vulnerability (or enhancing resilience) of environmental plantings to climate change. Diversity benefits can also be indirect, such as supporting a wide assemblage of beneficial/predatory insects to suppress pathogens and herbivorous insects (Landis et al., 2005).

Similarly, maximizing within-species genetic variation can enhance the resistance and resilience of reforested areas to climate change because plant populations respond differently to disturbances across climatic and altitudinal gradients (Bansal et al., 2015; Borzak et al., 2016). For example, in addition to locally sourced seed, seed can be sourced from populations that have similar mean annual temperature and precipitation to the projected climate of proposed environmental planting locations (Schueler et al., 2013; Booth, 2016). While selecting a diversity of species and genotypes may confer enhanced resilience for reforested areas, in some circumstances targeting species with a particular set of traits may improve outcomes. For example, in Australia's wet tropics the survival of species with high wood density was greater than species with low wood density, which was likely due to these species being better adapted to the high light and heat conditions typical of new revegetation sites (Charles et al., 2018). There are now tools available to design reforestation activities that select species with a suite of particular traits (Laughlin, 2014).

4.1.2. Vegetation structure

Along with species composition, vegetation structure is important for reforestation, both for meeting planting objectives and for reducing vulnerability to climate change. An important aspect of vegetation structure is stand density, as increasing stand density enhances carbon sequestration while controlling salinity and erosion. However, too high density can affect rates of carbon sequestration over long time-scales as overstorey biomass accumulates more slowly and understorey biomass declines with increased competition for resources (McHenry et al., 2006; Dwyer et al., 2010a, 2010b). High density stands can also take longer to reach biodiversity objectives as the overstorey can become functionally restricted, e.g. reducing the formation of tree hollows and large boughs (Vesk et al., 2008; Cunningham et al., 2015). They can also be at greater risk from climate change, as denser stands can have higher rates of transpiration, making them more susceptible to drought (Sohn et al., 2016). Indeed, thinning of dense stands has been demonstrated to enhance soil moisture content and productivity in retained trees (Whitehead et al., 1984; Sohn et al., 2016). Furthermore, wider spaced stands with larger individual trees are less susceptible to wind damage than denser stands of smaller trees (Galik and Jackson, 2009). Thinning may also encourage recruitment of additional woody species, if a seed source is available, thereby facilitating enhanced structural complexity and carbon sequestration (Dwyer et al., 2010a, 2010b). However, these outcomes are dependent upon the extent of thinning, with severe thinning potentially encouraging short-lived pioneer species, with negative consequences for longer-term rates of carbon sequestration (Dwyer and Mason, 2018). The net outcomes of thinning from a carbon perspective also need to consider the fate of thinned stems, particularly if left in-situ to decompose, thereby releasing carbon (Dwyer et al., 2009).

Structural complexity and age structure are also important components of vegetation structure that contribute to the vulnerability of reforestation projects. A diverse stand structure, i.e. with complexity in trees and shrubs, enhances both biodiversity and carbon sequestration outcomes (Kelty, 2006; Cunningham et al., 2015). A diverse age structure promotes resistance and resilience to climate change since multi-aged stands have more potential pathways for post-disturbance recovery (Millar et al., 2007; O'Hara and Ramage, 2013). A notable exception to this is fire risk, as more severe fires occur when vegetation structure increases the vertical connection between fuels, although landscape location and topographic position are also important considerations (Jenkins et al., 2016).

4.1.3. Establishment methods

Overall, vegetation structure and species composition are both strongly influenced by the methods used for establishing reforestation projects. Planting methods include planting of seedlings from tube-stock, direct seeding, natural regeneration or some combination of these methods. Direct seeding is often more economical and can incorporate a larger species diversity compared to planting seedlings (Palma and Laurance, 2015). Typically, direct seeding results in areas with high density, which allows for some mortality after germination (Schneemann and McElhinny, 2012, Palma and Laurance, 2015). However, if self-thinning is slow, this can slow development of structural attributes such as tree hollows and reduce carbon sequestration over long time-scales (Schneemann and McElhinny, 2012). In some circumstances self-thinning can take considerable time and intervention to thin may be warranted (Vesk et al., 2008).

Irrespective of the method used for reforestation, the germination and establishment phases of natural regeneration projects are perhaps associated with the highest risk. The extent of germination and rate of survival of seedlings will be dependent on weather conditions during these critical stages, particularly rainfall. Management actions that may enhance survival include ploughing prior to planting, which can be

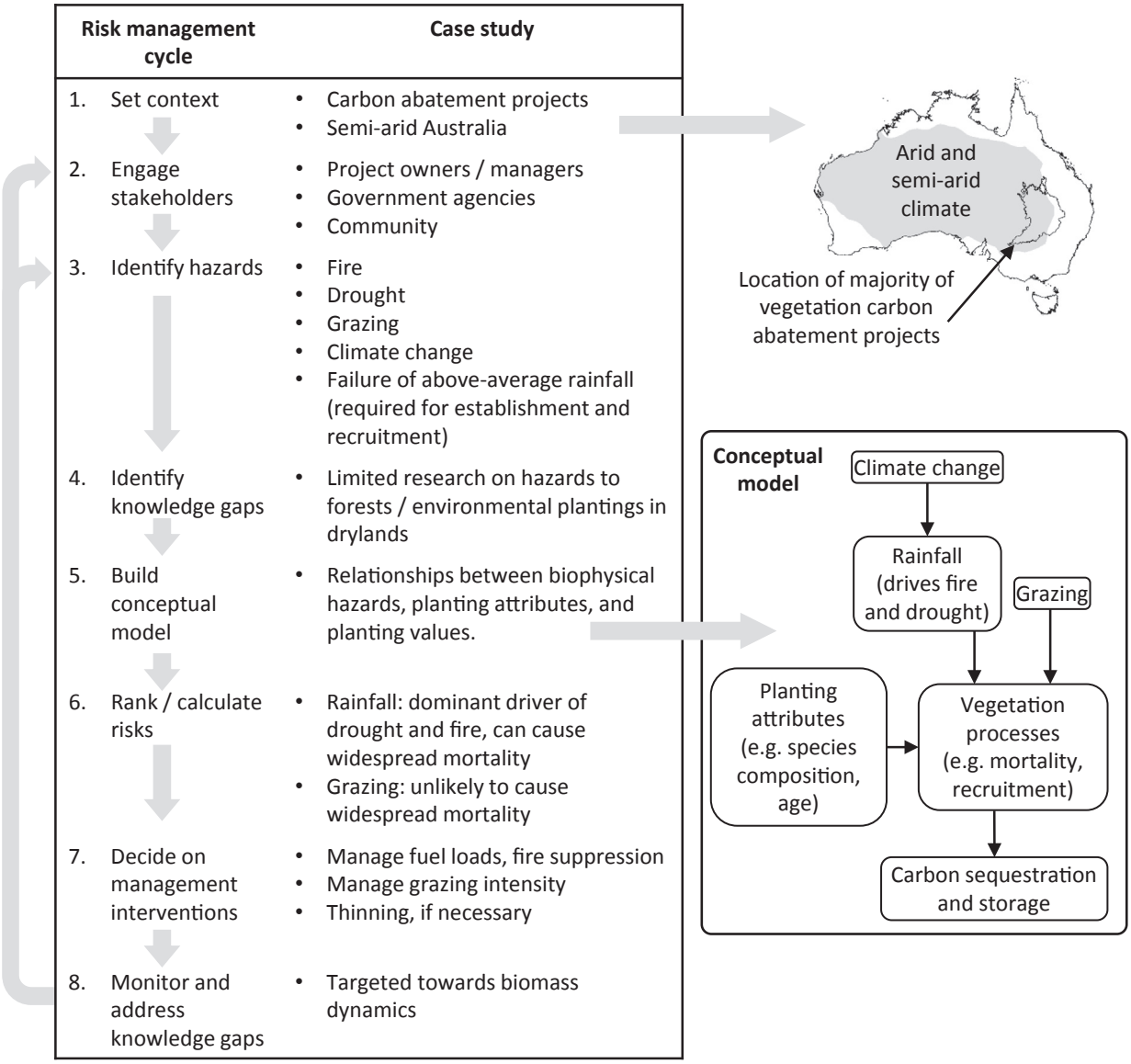
Risk management cycle
Case study
1. Set context
• Carbon abatement projects
• Semi-arid Australia
2. Engage stakeholders
• Project owners / managers
• Government agencies
• Community
3. Identify hazards
• Fire
• Drought
• Grazing
• Climate change
• Failure of above-average rainfall (required for establishment and recruitment)
4. Identify knowledge gaps
• Limited research on hazards to forests / environmental plantings in drylands
5. Build conceptual model
• Relationships between biophysical hazards, planting attributes, and planting values.
6. Rank / calculate risks
• Rainfall: dominant driver of drought and fire, can cause widespread mortality
• Grazing: unlikely to cause widespread mortality
7. Decide on management interventions
• Manage fuel loads, fire suppression
• Manage grazing intensity
• Thinning, if necessary
8. Monitor and address knowledge gaps
• Targeted towards biomass dynamics
Arid and semi-arid climate
Location of majority of vegetation carbon abatement projects
Conceptual model
Climate change
Rainfall (drives fire and drought)
Grazing
Planting attributes (e.g. species composition, age)
Vegetation processes (e.g. mortality, recruitment)
Carbon sequestration and storage

Fig. 4. Overview of the risk management cycle, modified from Burgman (2005) and the case study of carbon abatement plantings in semi-arid Australia.

beneficial by promoting deeper root penetration in seedlings (Galik and Jackson, 2009). Mulching and irrigation may provide short-term benefits but are likely to be impracticable at large scales, and irrigation may result in high mortality when removed (Fehmi et al., 2014). The use of seasonal forecasts may be beneficial to inform timing of reforestation, similar to agricultural systems (McIntosh et al., 2005). At the germination stage, an additional risk factor is the absence of fire, which may be required to break seed dormancy for some species (Clarke et al., 2013). This may be overcome by pre-treating seeds in direct seeding projects, or planting seedlings.

4.1.4. Size, shape and location

The size, shape and location of reforestation projects strongly influence the ability to meet objectives, obtain co-benefits and reduce vulnerability to climate change. Size and shape can act in opposite ways to deliver on the planting targets. For example, narrow and linear plantings have high edge to interior ratios, resulting in a high abundance of edge trees. Edge trees experience less competition for resources such as water, and therefore can have larger rates of carbon accumulation than interior trees (Paul et al., 2016). However, edge trees may be more vulnerable to wind damage and have greater exposure to biotic factors which may limit their growth, such as mistletoe (Bowen et al., 2009; Galik and Jackson, 2009). In contrast, block plantings may be more vulnerable to water stress, as there is greater competition for resources, and this may lower rates of carbon accumulation (Galik and Jackson, 2009). However, block plantings often support greater biodiversity values than narrow and linear plantings (Paul et al., 2016).

Location is also just as important. Risk factors vary spatially at small (e.g. gully versus ridge-top) and large (e.g. mesic versus arid climate) spatial scales. For example, ridge-top locations tend to be more vulnerable to mortality from fire and drought than gullies (Matusick et al., 2013), because gullies typically remain wetter for longer than ridge-tops and fires can spread rapidly upslope (Bradstock et al., 2010). At larger spatial scales, fire activity tends to vary across a productivity/aridity gradient, such that fire activity is lowest in arid and wet regions, limited by low biomass and moisture levels respectively, and highest in intermediate-productivity regions (Pausas and Ribeiro, 2013). Similarly, soil moisture varies topographically, typically being wetter in gullies than ridge-tops, and on polar facing slopes compared to equatorial facing slopes (Western et al., 1999). Identifying the primary risk factors under current and future climates is an important consideration when designing resilient environmental plantings. In particular, it is important to match species selection with planting location, e.g.

selecting fire-resistant species (i.e. those with thick, insulating bark, and the capacity to regenerate following fire) in fire-prone locations. Further, attributes of planting location, such as distance to established forest, slope, aspect and soil fertility can have a large influence on seedling establishment and growth, although the relatively importance of these factors will vary depending on the traits of species planted (Charles et al., 2018). Thus, the optimal size, shape and location of reforestation projects depends on (i) the primary purpose of the planting; (ii) the over-arching risk factors for a given site; and (iii) the traits of the species planted.

4.2. Managing risk in established reforestation projects

Managing risk involves the assessment of likely risks, prior to initiating any management interventions to mitigate those risks. Here, we use a case study of carbon offset projects in Australia to identify risk assessment approaches and interventions for existing reforestation projects.

4.2.1. Assessing risk in reforestation projects – a case study of carbon abatement in Australia

Assessing biophysical risks in reforestation projects is an on-going multi-step process that can be described by the environmental risk management cycle (Fig. 4). The first step (1) involves setting the context, followed by (2) engaging stakeholders, (3) identifying hazards, (4) identifying knowledge gaps, (5) developing a conceptual model of the system, (6) ranking/calculating risks, then (7) deciding on management interventions and (8) monitoring the effectiveness of those interventions and addressing knowledge gaps (Burgman, 2005). Here, we use a case study of reforestation projects established for carbon abatement in Australia to illustrate these steps in the risk management cycle (outlined in Fig. 4).

Under the Australian Emissions Reduction Fund, AUD$2.55 billion was set aside for carbon abatement projects over three years (Australian Government, 2014). A range of types of vegetation projects could receive funding under this scheme, including (but not limited to) environmental plantings of native species, forest regeneration, and avoided deforestation (Australian Government, 2014). Of the vegetation projects funded by the scheme, over 75% occur in the semi-arid region of eastern Australia (Fig. 4; http://www.cleanenergyregulator.gov.au/ERF, accessed 01/11/2017). All of the vegetation projects have a permanence period, typically 100 years (Australian Government, 2014). Given the long project lengths of these carbon abatement projects, a major concern is that vegetation will produce net carbon emissions, or will fail to meet projected rates of carbon sequestration over the life of a project. Those with a stake in ensuring project success through appropriate risk management include the land managers who own or manage the carbon abatement projects, those government agencies explicitly involved in the oversight of these projects, or in land management more generally, and the wider community for whom climate change abatement is an important environmental goal.

Biophysical hazards to carbon projects include anything that may reduce productivity, trigger mortality, or prevent recruitment and/or establishment of seedlings in new plantings. In the semi-arid region of Australia where these projects occur, the primary hazards are disturbances like fire, drought and grazing, particularly by livestock and wild goats, which can reduce productivity and trigger mortality, depending on disturbance intensity (Nolan et al., 2018a). In addition, seedling establishment in this region relies upon the above-average rainfall that occurs during infrequent wet years (Friedel et al., 1993). Climate change will influence most of these risk factors to some extent, primarily through changes in rainfall and the effects of elevated temperature on evaporative demand and soil water availability. In this region mean annual rainfall is projected to increase, particularly in the wetter, summer months, but may decrease during the drier spring months (Olson et al., 2016). Reliable risk assessment in this semi-arid system is challenged by considerable knowledge gaps, primarily the lack of research on forests and environmental plantings in drylands, as most research has been concentrated in more mesic environments (Nolan et al., 2018a). Monitoring and research to address knowledge gaps should be targeted towards biomass dynamics as the primary values of reforestation projects are in carbon sequestration.

A conceptual model of risk to carbon abatement projects would incorporate relationships between these biophysical hazards, attributes of the vegetation, such as species composition and age, and effects on carbon storage and rates of carbon accumulation (Fig. 4). This conceptual model could then be used as the basis to rank the relative importance of hazards. In this region, rainfall is the key driver of most disturbances and subsequent vegetation processes, with the exception of grazing (Nolan et al., 2018a, 2018b). Thus, rainfall patterns and grazing impacts are the two primary risks to carbon offset projects. There is a range of potential interventions for managing risk to reforestation projects in these landscapes, including managing fuel loads, grazing intensity and planting density, detailed below (Section 4.2.2).

4.2.2. Management intervention options

Buffering reforested areas from disturbance primarily occurs at the scale of individual projects, but may also be warranted at a landscape scale (Table 2). For example, while fuel reduction activities aimed at preventing the spread of wildfire can be applied at the scale of individual projects, it is the matrix of fuel loads across a landscape that are important in driving the spread of large fires (Collins et al., 2015; Jenkins et al., 2016). Fuel reduction activities can include controlled fires to reduce understorey fuel loads, and pruning of ladder fuels, like low branches (Cruz et al., 2017). However, fuel management treatments aimed at reducing the rate of spread of wildfires are known to reduce in efficacy over time (Price et al., 2015). Fire suppression activities are another available intervention, most likely effective for containing smaller-sized and/or lower intensity fires, requiring access to fire suppression resources (e.g. personal protective equipment, firefighting equipment, and access to water) and well-maintained fuel breaks (Penman et al., 2013).

Improved resistance and resilience of established reforested areas can be achieved by within-stand actions, like managing stand density or promoting structural and compositional diversity. Intervention options include thinning or planned disturbances such as controlled burns. Controlled burns can trigger recruitment, and thus promote a diverse age and stand structure. Controlling grazing pressure may also be effective. For example, strategic grazing in high-productivity pastures may facilitate woody seed germination and establishment (Vesk and Dorrough, 2006), while restricting grazing in drier environments, particularly when plants are within browse height, may increase aboveground biomass (Eldridge et al., 2016). Grazing of domestic livestock and wild herbivores may be controlled through a variety of methods including fencing, controlling artificial access to water, and protection of wild predators that may then influence densities and behaviours of grazing mammals, although this has not been widely tested (Johnson and Wallach, 2016). It is worth noting that many of the management options outlined here can be expensive, which may prohibit their implementation across large areas.

5. Managing reforestation activities at a regional and national scale

A number of approaches for reducing the vulnerability of reforested areas at regional and national scales present themselves. They range from selecting locations for new plantings to monitoring protocols for existing plantings (Table 2). Suitable locations for reforestation depend on their purpose. For example, biodiversity plantings may target locations that enhance connectivity between remnant patches of vegetation that are critical for endangered species. Carbon plantings may target regions of high productivity that are capable of sequestering large

amounts of carbon, or low productivity regions, such as arid and semi-arid regions, which are spatially extensive and thus offer more potential opportunities for establishing reforestation projects (Lal, 2004). For example, arid and semi-arid regions cover 70% of Australia (Fig. 4). Where vulnerability maps exist, those that integrate climate projections as well as soil and vegetation conditions at regional and national scale can assist with selecting locations for reforestation. Selection should target areas with low frequencies of current or projected disturbance, or with high connectivity between patches of vegetation to facilitate species movement and gene flow to enhance resilience (Millar et al., 2007). Large-scale reforestation with woody perennial species, as promoted by the emissions reduction scheme, will have a long-lasting effect on the landscape. Decisions made now, particularly around project location and design, will strongly influence future vulnerabilities to disturbances of both reforested areas and remnant vegetation. It is critically important these projects are managed adaptively, which requires monitoring of relevant attributes to inform ongoing management towards project goals and to inform decision-making for future projects.

6. Decision support systems and modelling

Although large areas have already been, or are likely to be, revegetated with trees in Australia, there are no national protocols in place to track, monitor or evaluate their outcomes (Bradshaw et al., 2013). This is a particularly notable problem because forest services and their value will change over time. It is necessary to quantify these changes to understand the worth of plantings at any given time, and how that worth may be at risk. It is also necessary to audit plantings to assesses the extent to which they have met project goals, and what the causes are of plantings either failing to meet these goals, or conversely, exceed goals

The complexity of managing reforested areas for multiple benefits, over long time periods renders it virtually impossible to properly capture and understand outcomes and risks without an adequate framework of analysis. Decision support tools (e.g. Pichancourt et al., 2014) that incorporate assessments of potential outcomes from established forest as well as process-based hydrological and forest growth models or bioclimatic models can be harnessed to quantify impacts of biophysical threats and disturbances (Pinkard et al., 2010; Barry and Pinkard, 2013; Eyles et al., 2013; Pichancourt et al., 2014). Despite widespread recognition that reforestation may provide considerable environmental services, very little quantification of the value of these services to whole farm and regional economies has been conducted. This may critically affect decision-making processes, particularly when information around risk is unaccounted for. For example, the key barriers to farmers participating in reforestation activities under Australia's carbon emissions reduction scheme include uncertainty around costs and the policy landscape (Kragt et al., 2017). Community apprehension about participating in reforestation activities, including those for carbon sequestration, may also be due in part to financial losses associated with historical plantation schemes (Anderson et al., 2013; Semple, 2013) or poor public perception (Dye 2013). Thus, there is scope for developing approaches that better quantify the economic implications of reforestation at farm and regional scales, including the costs and effectiveness of management actions.

7. Conclusions

Reforestation can achieve significant environmental and economic co-benefits and assist nations in meeting carbon abatement targets. However, as shown in this review, reforestation for offsetting carbon emissions is not without risk, especially given the uncertainty introduced by climate change. Once forests are established intervention becomes difficult and costly. Thus, there are important decisions to be made at the planning stage about planting location and species composition, to best encourage resilience of plantings to climate change. We have suggested that, depending on the degree of confidence of future climates at the location of a planting, that strategies may involve diversifying genotypes and targeting specific species traits to match the anticipated future climate. We also suggest that a multi-scale approach to planning is important: focussing within project on attributes and design, including project size, but also planning projects in the context of a portfolio of projects at a national, regional and catchment scale, such that the risk across the whole portfolio of substantial loss is reduced. It is recognised that at the project level some trade-offs may be involved between the rate of carbon accumulation and the project risk, for example initial planting density. These are individual proponent decisions but we note the important role that decision support tools can play in quantifying the risk/reward of different strategies. Finally, we note that permanence periods for reforestation activities can be long and that integration of carbon projects into whole farm planning or regional NRM objectives will minimise future economic regrets and challenges to social licence.

8. Declaration of interest statement

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